Visible light as a communication medium – from illumination to data transmission

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The fast development of new Li-Fi (Light-Fidelity) technology based on the unique physical properties of visible light will make it possible to build high-speed telecommunications networks with high cell density, compatible and complementary RF networks. The use of visible light for data transmission allows each LED luminaries to be used as an Internet access point (AP) where the data is transmitted at speeds unattainable on Radio networks (RF); each user will be able to move between the light sources, without interrupting the flow of the transmitted data and interception (wiretapping) of the provided information will be impossible. The realization of these solutions is achieved by using versions of OFDM and novel algorithms for light intensity processing. .

Видимата светлина като комуникационна среда – от осветление към предаване на данни (Борис Йовчев, Росица Младенова)*. Бързото развитие на новата Li-Fi (Light-Fidelity) технология, основана на уникалните физически свойства на видимата светлина, ще направи възможно да се изграждат високо скоростни телекомуникационни клетъчни мрежи с голяма плътност, съвместими и допълващи RF мрежите. Използването на видимата светлина за предаване на данни дава възможност всяко осветително тяло да се използва и като Интернет точка за достъп (AP), където данните се предават със скорости, непостижими за радио мрежите (RF); всеки потребител ще може да се движи между източниците на светлина , без да се прекъсва потока на предаваните данни, а прехващането (подслушването) на информацията ще бъде невъзможно. Реализирането на тези решения се постига с използването на нови варианти на модулацията ортогонално мултиплексиране с честотно разделяне (OFDM) и разработването на сложни алгоритми за обработка на интензивността на светлината.*

Introduction

On June 3, 1880, Bell's assistant transmitted a wireless voice telephone message from the roof of the Franklin School to the window of Bell's laboratory, some 213 meters away. Bell believed the photophone was his most important invention. Of the 18 patents granted in Bell's name alone, and the 12 he shared with his collaborators, four were for the photophone, which Bell referred to as his *'greatest achievement'*, telling a reporter shortly before his death that the photophone was *"the greatest invention [I have] ever made, greater than the telephone"*.

The photophone was similar to a contemporary telephone, except that it used modulated light as a means of wireless transmission.

The brightness of a reflected beam of light, as observed from the location of the receiver, therefore varied in accordance with the audio-frequency variations in air pressure - the sound waves - which acted upon the mirror. In its ultimate electronic form, the photophone receiver used a simple selenium cell at the focus of a parabolic mirror [1], Fig.1.

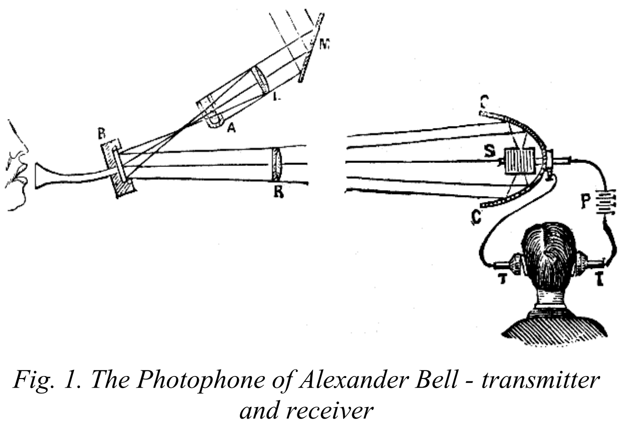
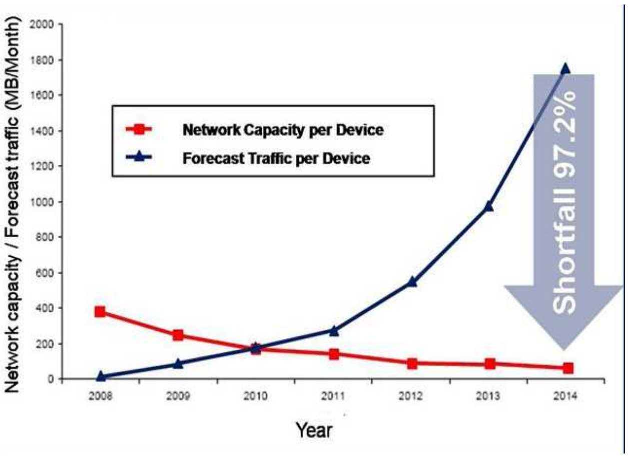


Fig. 1. The Photophone of Alexander Bell - transmitter and receiver

The cell's electrical resistance (between about 100 and 300ohms) varied inversely with the light falling upon it. The selenium modulated the current flowing through the circuit, and the current was converted back into variations of air pressure—sound—by the earphone. This was the world's first formal wireless telephone communication, thus making the photophone the world's earliest known radiophone and wireless telephone systems. Bell and Tainter had devised some 50 different methods of modulating and demodulating light beams for optical telephony. Despite the recent improvements made in the company Bell Telephone, the achieved parameters of radio communications developed by Marconi surpassed those of Photophone and its further development has been delayed.

More than 130 years after the photophone first came to light, professor Harald Haas is pioneering his own light-centric wireless communications technology. And ironically, he's doing so in the Alexander Bell building at the University of Edinburgh in Scotland. The term Li-Fi was coined by prof. Harald Haas, and refers to visible light communications (VLC) technology. Motivated by the looming exhaustion of radio (RF) spectrum, he set out the aim to prove that optical wireless communication (OWC) are a viable alternative solution to this major problem.

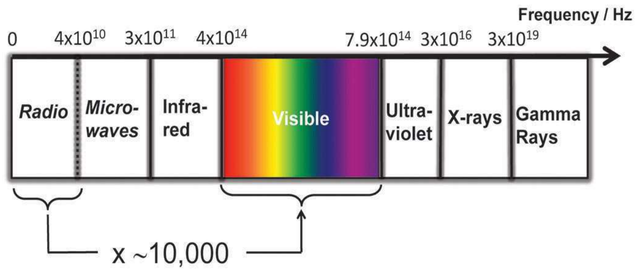
Wireless data traffic is increasing exponentially [2]. Despite the continuous improvements in wireless communication technology, it is expected that the future demand cannot be met because the radio frequency spectrum has been almost completely utilised. This exponentially growing demand, see Fig. 2, is the main challenge for wireless communications over the next decades.



Фиг. 2. The predicted, almost exponential, increase in demand of mobile communications services over the next years, and the corresponding network capacity evolution.

Founded back in 2012 by Prof. Harald Haas and his team (which also employs three Bulgarian scientists) pure Li-Fi develops technologies for secure, reliable, high-speed optical wireless communication networks. The company is a spin-off from the University of Edinburgh.

Light fidelity (Li-Fi), the high-speed communication and networking variant of visible light communication (VLC), aims to unlock a vast amount of unused electromagnetic spectrum in the visible light region see Figure 3 [3].



Фиг.3. The electromagnetic spectrum and the vast potential of unused, unregulated, safe green spectrum in the visible light part. The visible light spectrum is 10,000 times larger than the entire radiofrequency spectrum.

Li-Fi works as a signal transmitter with the off-the-shelf white LEDs typically used for solid-state lighting and as a signal receiver with a p-i-n photodiode or avalanche photodiode. LEDs have necessary for that purpose property that can be switched at a very high speed. This means that Li-Fi systems can illuminate a room and at the same time provide wireless data connectivity. In connection with the further increasing of speed, it is developing new types of light-emitting diodes.

The new Li-Fi technology has not yet been brought to the wide application because it is facing a number of technical challenges still to be addressed. As an example, we will look through the essential of them relating to:

The modulation

Unlike laser diodes, the LEDs produce incoherent light, which means the signal phase cannot be used for data communications. Therefore, the only way to encode data is to use intensity modulation and direct detection (IM/DD).

Early work in the field suggested on-off keying (OOK) and pulse position modulation (PPM) as viable techniques. However, the bandwidth of the front-end elements and the optical channel is limited. This leads to the requirement for multi-level schemes like unipolar pulse-amplitude modulation (PAM) in order to achieve higher throughput. As the communication speeds increase, the limited communication bandwidth leads to inter-symbol interference (ISI). Hence, a more sophisticated scheme like orthogonal frequency division multiplexing (OFDM) becomes the prime candidate for VLC.

At OFDM, the available bandwidth is divided into multiple carriers, each of which is modulated with a quadrature amplitude modulation (M-QAM), see фиг.4 [4].

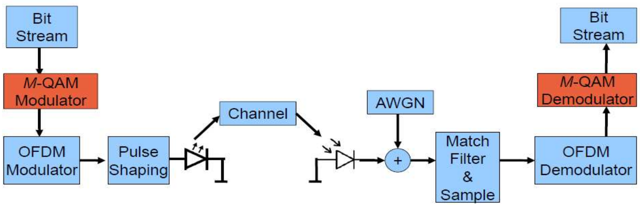


Fig. 4. A communication system based on OFDM.

OFDM is similar to the systems with frequency division, but in contrast to them uses much more effectively the available spectrum, since the necessary spacing between the frequencies is much less. This is achieved when the transmitted signals are orthogonal to one another, thus eliminating the interference between adjacent carrier frequencies.

The conventional OFDM generates complex bipolar signals. Therefore, modifications have to be made before it becomes suitable for VLC, see Fig 5.

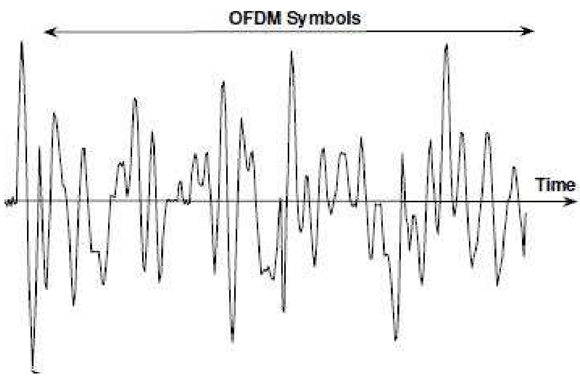


Fig. 5. Bipolar OFDM signal

The bipolar signals are a problem in Li-Fi, as LEDs must be controlled by real-value signals.

A number of different techniques for the creation of unipolar signals exist. A straightforward approach is called direct-current biased optical OFDM (DCO-OFDM). It involves the addition of a bias current to the bipolar signal, making it unipolar [5], see Fig. 6.

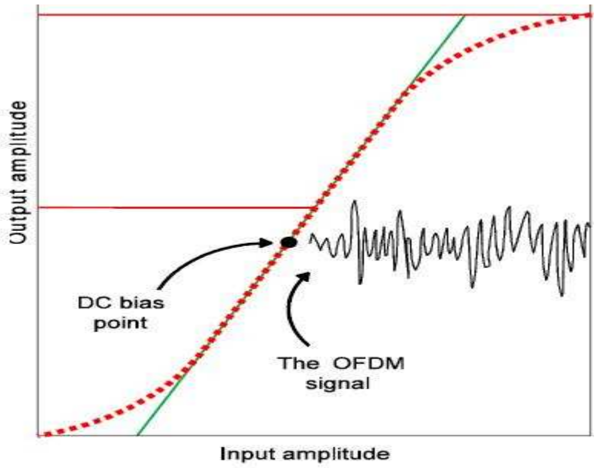


Fig. 6. Optical OFDM with DC bias DCO-OFDM

However, the addition of the direct current (DC)-bias increases the power dissipation of the time domain signal significantly when compared to the bipolar case.

In order to avoid this DC bias, alternative techniques such as asymmetrically-clipped optical OFDM (ACO-OFDM) exploit the properties of the OFDM frame to generate a signal which does not need biasing. In ACO-OFDM, only the odd subcarriers in the frequency domain are modulated, which leads to a symmetric time domain signal. The symmetry allows negative values to simply be set to zero without affecting the encoded information as all distortion falls on the even subcarriers in the frequency domain. Similar approaches which exploit different properties of the OFDM frame, but effectively achieve the same result are: pulse-amplitude modulated discrete multitone modulation (PAM-DMT).

Recently, a third technique known as unipolar OFDM (U-OFDM) has been proposed by the University of Edinburgh. It takes a real bipolar OFDM signal and generates a unipolar signal by splitting every OFDM frame (**B**) into two separate frames in the time domain [6]:

1. The first frame (**P**) contains the positive time-domain samples and zeros in place of the negative samples.
2. The second frame (**N**) contains only the absolute values of the negative samples and zeros in place of the positive samples.

The common disadvantage of these technologies is the loss of 50% in spectral efficiency, i.e. the data rate is reduced by half.

A novel modulation technique coined SIM-OFDM was recently proposed. SIM-OFDM uses different frequency carrier states – active and non-active to convey information and leads to increased performance in comparison to conventional OFDM. Additionally, its innovative structure can lead to a decrease of the system power peak, and avoids bit error propagation whilst retaining the benefits of the concept [7].

However, no significant progress has been made until now. University of Edinburgh has recently developed a new technique which allows the spectral efficiency loss to be avoided.

Driver Technology

Many of the current standardisation efforts have focused on using constant current drivers. There are three main reasons to drive LEDs with constant current:

• To avoid violating the Absolute Maximum Current Rating and compromising the reliability.

• To obtain predictable and matched luminous intensity and chromaticity from each LED.

• To optimize the energy efficiency of the driver circuit.

Until now, the energy efficiency of the driving circuitry has been critical since it was merely a power converter stage. However, Li-Fi re-purposes this technology to provide communications. As a consequence, to attain the benefits of the latest developments in optical wireless modulation techniques, a variable current driver must be implemented. Qualifying the exact impact of OOFDM modulation and a variable current driver on the life-span of the LED chip and the energy efficiency optimization of it are an open research area.

Backbone Network

A high throughput backbone network is essential to facilitate the large data densities envisioned in a Li-Fi system. The backbone network, however, along with data must also provide power to each Li-Fi AP to minimise the amount of cabling. Power line communications (PLC) is also a viable alternative, but can undermine the inherent security of a Li-Fi network by disseminating information throughout the power grid.

Bidirectionality

Most demonstrations of VLC technology until now have focused on maximising the communication speed over a point-to-point, *unidirectional* channel. However, to realise the envisioned Li-Fi communication systems, the establishment of bidirectional communication is essential, *i.e.*, uplink transmission. This is not straightforward, as employing the same VL band in both directions would result in large self-interference at a transceiver due to crosstalk, unless physical separation of the photo diode (PD) and LED can be incorporated. However, the utilisation of infra-red links to separate the channels in frequency has led to promising results

At the World Congress of mobile communications MWC 2014 and CeBIT 2014 the pure LiFi company submitted the system Li-1st, demonstrating full-duplex communication [8], see Fig. 7.

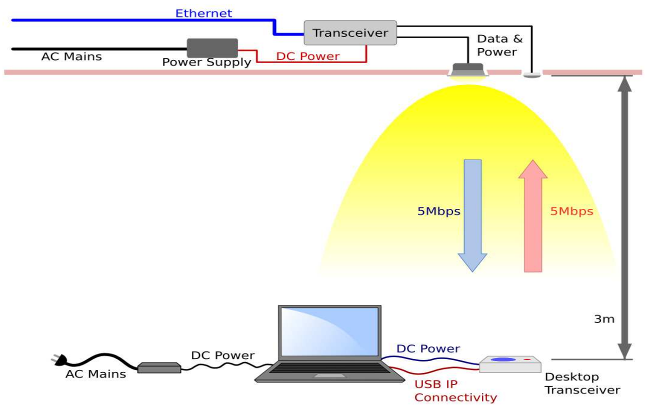


Fig. 7. Li-1st system

The Li-1st allows you to network via a desktop photosensitive unit that works in tandem with an off-the-shelf, unmodified LED light fixture. The desktop unit has infrared LEDs to communicate in the uplink channel. The product offers full duplex communication with a capacity of 5Mbps in both the downlink and uplink over a range of up to three metres, while simultaneously providing ample desk space illumination. The distance achieved by the system depends only on the strength of the light source, i.e., the LED light. Li-1st offers a simple plug-and-play solution for secure wireless point-to-point Internet access with a wide range of LED luminaires.

Multiple access

Networking cannot be decided without proper scheme for multi-user access, which allows users to share communication resources without mutual eavesdropping (cross-talk). The used in radio communications for multi-access schemes can be adapted for optical wireless channels, if they fulfill the necessary modifications in terms of the intensity modulation and direct detection (IM / DD). For this purpose the extension of OFDM - OFDMA

(Orthogonal Frequency-Division Multiple Access) - orthogonal frequency division multiplexing for sharing access is used.

In Q4 of 2014, the pure LiFi team launched and shipped the world's first Li-Fi network product – Li-Flame – to industry customers worldwide. The system turns off-the-shelf light fixtures into Li-Fi access points that can simultaneously communicate to a plurality of users in a bi-directional fashion. It also consists of the world's first battery powered Li-Fi mobile unit which is attached to a laptop screen and allows user roaming within a room, or indeed an entire building. The technology Li-Flame provides data density significantly greater than Wi-Fi [9].

LI-FI attocell (atto -10^{-18})

In the past, wireless cellular communications has significantly benefited from reducing the inter-site distance of cellular base stations. By reducing the cell size, the network spectral efficiency has been increased by two orders of magnitude in the last 25 years. More recently, different cell layers composed of microcells, picocells and femto cells have been introduced. However, the uncoordinated and random deployment of small cells also causes additional inter- and intra-cell interference which imposes a limit on how dense these small RF can be deployed before interference starts offsetting all frequency reuse gains.

The small cell concept, however, can easily be extended to VLC in order to overcome the high interference generated by the close reuse of radio frequency spectrum in heterogeneous networks. The optical AP is referred to as an attocell.25 Since it operates in the visible light spectrum, the optical attocell does not interfere with the microcellular network. The optical attocell not only improves indoor coverage, but since it does not generate any additional interference, it is able to enhance the capacity of the RF wireless networks. The user data rate in attocell networks can be improved by up to three orders of magnitude.

Moreover, Li-Fi attocells can be deployed as a part of a heterogeneous VLC-RF network as illustrated in Fig. 8.

They do not cause any additional interference to RF macro- and picocells, and can, hence, be deployed within RF macro-, pico- and even femtocell environments. This allows the system to vertically hand-off users between the RF and Li-Fi sub-networks, which enables both free user mobility and high data throughput.

Fig.8. Optical Network with atto-cells - achieving high energy efficiency of the existing infrastructure operation.

Cellular network

The deployment of multiple Li-Fi attocells provides ubiquitous data coverage in a room in addition to providing nearly uniform illuminance. This means that a room contains many attocells forming a very dense cellular attocell network. Each atto-cell covers an area of 1-10m2 and distance of about 3m. A network of such density, however, requires methods for intra-room interference mitigation while there is no inter-room interference if the rooms are separated by concrete walls. The unique properties of optical radiation, however, offer specific opportunities for enhanced interference mitigation in optical attocell networks. Particularly important is the inability of light to penetrate solid objects, which allows interference to be managed in a more effective manner than in RF communication. The VLC interference mitigation caused by solid objects in a typical indoor environment leads to a tremendous increase in area spectral efficiency (ASE) in в bits/s/Hz/m^2.

The power of a typical LED light bulb

Professor Harald Haas and his team have made another breakthrough in Li-Fi by demonstrating that up to 1.1 gigabit per second (Gbps) can now be transmitted using light waves from micro LEDs over a distance of 10 metres using less than 0.5W power. This is only 5% of the power of a typical 10W LED light bulb. This proves the point that lights can be dimmed down (almost switched off) while high data rates and coverage are maintained.

Conclusion

Research in VLC over the past ten years has primarily been focused on finding an optimum modulation scheme for IM/DD assuming point-to-point VLC links by taking into account that VLC may serve two simultaneous functions:

(a) Illumination, and

(b) Gigabit wireless communication.

The predominate sources for signal distortion are frequency dependent in such systems. This constitutes one key reason why there is now a general understanding that OFDM is the most suitable choice as a digital modulation scheme for Li-Fi, and there are good technical reasons to reconsider the IEEE 802.15.7 VLC standard. The straightforward multiple access technique that OFDMA provides at almost no additional complexity and its compatibility to state-of-the art wireless standards like LTE and IEEE 802.11 further favor the selection of this modulation/multiple access scheme. The realization of a bidirectional connection also seems to have been addressed successfully to an extent that the first commercial bidirectional point-to-point Li-Fi systems are available. The most practical solutions to the uplink channel realization is to consider the IR or RF spectrum. The confidence brought by encouraging recent research results and by the successful VLC link-level demonstrations, has now shifted the focus towards an entire Li-Fi attocell networking solution. The unique physical properties of light promise to deliver very densely-packed high-speed network connections resulting in orders of magnitude improved user data rates. Based on these very promising results, it seems that Li-Fi is rapidly emerging as a powerful wireless networking solution to the looming RF spectrum crisis, and an enabling technology for the future Internet-of-Everything.

Based on past experience that the number of wireless applications increases by the square of the number of available physical connections, Li-Fi could be at the heart of an entire new industry for the next wave of wireless communications.

It is necessary however still a lot of efforts to overcome the discussed challenges concerning Li-Fi technology. It follows that there is also a possibility and necessity **in Bulgaria to be organized scientifical and technical research (R & D)**, in order to prepare specialists in this promising technical field of telecommunications, business services and operation of relevant new products and systems.

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